Renewable and Sustainable Energy Reviews 38 (2014) 20–35

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

How car material life-cycle emissions are considered in environmental rating methodologies? Suggestion of expedite models and discussion

Gonçalo N. Correia, Teresa P. Batista, Sara S. Marques, Carla M. Silva *

IDMEC/LAETA-Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais, 1, 1049-001 Lisboa, Portugal

ARTICLE INFO

Article history:
Received 12 February 2014
Received in revised form
16 April 2014
Accepted 17 May 2014
Available online 14 June 2014

Keywords:
Environmental rating methodologies
Embodied materials life cycle
Alternative light-duty vehicle technologies
External costs

ABSTRACT

This paper reviews existing vehicle environmental rating methodologies worldwide and focuses on how these methodologies deal with alternative vehicle technologies (plug-in vehicles, hybrid vehicles, and fuel cell vehicles) and emissions of greenhouse gases (CO_2, N_2O, and CH_4) and pollutants (NO_x, VOC, CO, SO_x, PM_{10} and $PM_{2.5}$) derived from embodied materials life cycle. United States, Mexico, Europe and Australia have public access data and websites with top 10 rankings. The ways the scores are calculated for each vehicle have differences in what regards the considered boundaries for the emissions analysis. In Europe, there is still not a unique rating methodology or ranking system, e.g., Belgium, Germany and United Kingdom have their specific scoring schemes. Multilinear regression models were developed as an attempt to estimate the vehicle embodied emissions as a function of vehicle lifecycle mileage, electricity mix, vehicle mass, battery mass and fuel cell power to cope with different production regions and different alternative vehicle technologies. The regression models were validated against Volkswagen life cycle assessments (LCAs), and compared against American Council for an Energy Efficient Economy (ACEEE) – Green Book linear functions for material assessment and UK 12 material dataset for materials assessment. The developed models proved to be useful in applications related to rating methodologies using life-cycle concepts, with good reliability for comparisons considering the complexity of processes involved in vehicle materials life-cycle assessment.

Contents

* Corresponding authors.
E-mail address: carla.silva@tecnico.ulisboa.pt (C.M. Silva).

http://dx.doi.org/10.1016/j.rser.2014.05.055
1364-0321/

1. Introduction

Road passenger vehicle fleet has a significant impact on energy consumption and, consequently, due to the dominant internal combustion technology, in greenhouse gas (GHG) and pollutant emissions worldwide. In 2010, the transport sector consumed about 2200 million tons of oil equivalent (mtoe), constituting around 19% of the global energy supplies [1]. More than 60% of the oil consumed goes to the transportation sector. Road transport accounts for the bulk, around 76% of the total transportation energy consumption [1]. The light-duty vehicles (LDVs), including light trucks, light commercial vehicles, and minibuses, accounted for 52%, while trucks, including medium- and heavy-duty ones, accounted for 17% [1]. Due to this reality, both public transportation and more efficient light-duty vehicle technologies are being considered ([2–4]).

Concerning light-duty vehicles, several methods for informing car end users are accessible by means of an informative label at purchasing spots, or through websites dedicated to attributing scores and providing lists with the ranks of commercial available vehicles in each country. For example in Europe, first sale vehicles must have an environmental rating sticker, which among other parameters shows the CO_2 emission and the fuel consumption of the vehicle while in usage [5], see Fig. 1, as part of the action plan for the Directive 2012/27/EU. In United States it is mandatory that the car on sale has a label, which focuses on fuel economy, fuel costs and environmental impacts related to smog and GHG [6], see Fig. 2 An extensive review of existing labels worldwide can be found in Mahlia et al. [7]. The focus is usually on in-use CO_2 tailpipe emissions.

Despite the main methods used to raise awareness about consumers' purchasing decisions and encourage manufacturers to explore more efficient powertrains such as car labeling and environmental rankings, the main methodology used by the scientific community is life cycle assessment (LCA).

The LCA methodology was developed to evaluate the mass balance of inputs and outputs of systems and to organize and convert those inputs and outputs into environmental themes or categories relative to resource use, human health and ecological areas. The quantification of inputs and outputs of a system is called Life Cycle Inventory. The process of making an LCA can be divided into four phases according to ISO 14001:

- Phase 1: Definition of purpose, goal, functional unit and system boundaries.
- Phase 2: Inventory analysis, including data collection for all processes (input and output data) and allocation or system expansion between product and co-product.
- Phase 3: Evaluation of the environmental effects, including calculation of the LCA results through classification and characterization.
- Phase 4: Interpretation of the result and identification of significant issues.

The LCA of a car can be composed by the fuel life cycle (well-to-wheel, WTW) and by the embodied materials life cycle. The last one is particularly important with the increasing electrified technologies. The vehicle embodied materials life cycle analysis potentially includes raw materials extraction, production, assembling, dismantling and recycling, and some components have a more significant impact than others; for instance, batteries and fuel cells have higher impact than internal combustion engine (ICE) or electrical motor due to the material in their constitution, considering for instance nickel metal hydride and lithium-ion materials for batteries and graphite, aluminum and carbon sheets for fuel cell stack [8]. This life cycle part can represent as much as 6–17% of the total GHG emissions ([8–13]) and is especially important for electrified technologies like pure electric vehicles (EVs), hybrid vehicles (HEVs), plug-in hybrid vehicles (PHEVs) and fuel cell-based vehicles (FCHEVs or FCPHEVs).

Materials life cycle may be assessed using for example Ecoinvent database in Simapro [14] or using GREET ([15,17]). While Simapro is a generic software that has life-cycle inventory databases and impact assessment methods, and follows the LCA four phases described above, therefore allowing it to assess life-cycle impact from different perspectives of a material or product, GREET is specific for light-duty vehicle life cycle ([18,15]). GREET stands for Greenhouse gas Regulated Emissions and Energy use in Transportation, and is basically an inventory dataset specific for the fuels that feed the cars “fuel cycle” and for the materials used in the cars itself “vehicle cycle”. It returns inventory values for GHG, energy consumption and criteria pollutants.

Hawkins et al. [16] provide an assessment of the completeness of the literature in describing the full life cycle of HEV, PHEV and EV vehicles, excluding hydrogen-based technologies: production of the vehicle itself; the in-use phase; production and distribution of the in-use phase energy consisting of transmission, and distribution of electricity or other fuels; and end of life. It reviews 51 studies including different scopes (vehicle production, battery production, electronics production, recycling, disposal, use patterns, electricity/fuel production, maintenance, electric grid, and dynamic grid), emissions (CO_2, NO_x, CO, SO_2, PM, N_2O, HC, VOC, and CH_4), impact categories (global warming potential – GWP, or greenhouse gas – GHG, acidification potential, eutrophication potential, human toxicity potential) and resource use (energy use, fuel use, metals use and water). An extensive review of hydrogen base technologies LCA studies and WTW studies can be found in Geerken et al. [19]. This covers 100 papers in the field, not including the PHEV technology. The LEM main report [20] and Lipman and Delucchi [21] have studied several vehicles and countries, including road infrastructure but also not including PHEV. A PHEV detailed analysis can be found in Elgowainy et al. [17] and reviewed in Lipman and Delucchi [21].

These review studies allow concluding that the majority of the research works focus on the fuel life cycle (well-to-wheel, WTW) part of the vehicle life cycle, on energy use and GHG or CO_2 equivalent emissions. Few studies report indicators such as acidification potential (AP), human toxicity potential (HTP) or eutrophication potential (EP). This way the comparison of the alternative vehicle technologies is made by means of an environmental category only, the climate change.

Despite the ISO 14040-series discouraging the use of single scores, they are useful to better compare the environmental performance of two or more products. For example the Ecoindicator 99 method (included in Simparo) considers 11 impact categories related to Human Health, Ecosystem Quality and Resources (see Fig. 3). The impacts are then normalized and weighted to give a single score function of the chosen perspective: hierarchist, egalitarian, or individualist. By nature the method can be dubious due to its inherent subjectivity, but can be extremely useful for comparison purposes.

Environmental scoring methodologies can be based on LCA principles but usually use monetized external damages for each pollutant [22] and usually global warming potential and air quality categories. Again they use single score indicators for comparing vehicles' environmental performances (see Fig. 5 as an example). Other methods used by manufacturers allow comparing only vehicles of the same model. For instance Ford Product Sustainability Index (PSI) allows comparing several Ford models and is based on life cycle assessment (LCA) principles, but chose 8 indicators to compare the sustainability of the vehicles, as shown in Fig. 4. It adds the social and economic dimensions to the products' sustainability.

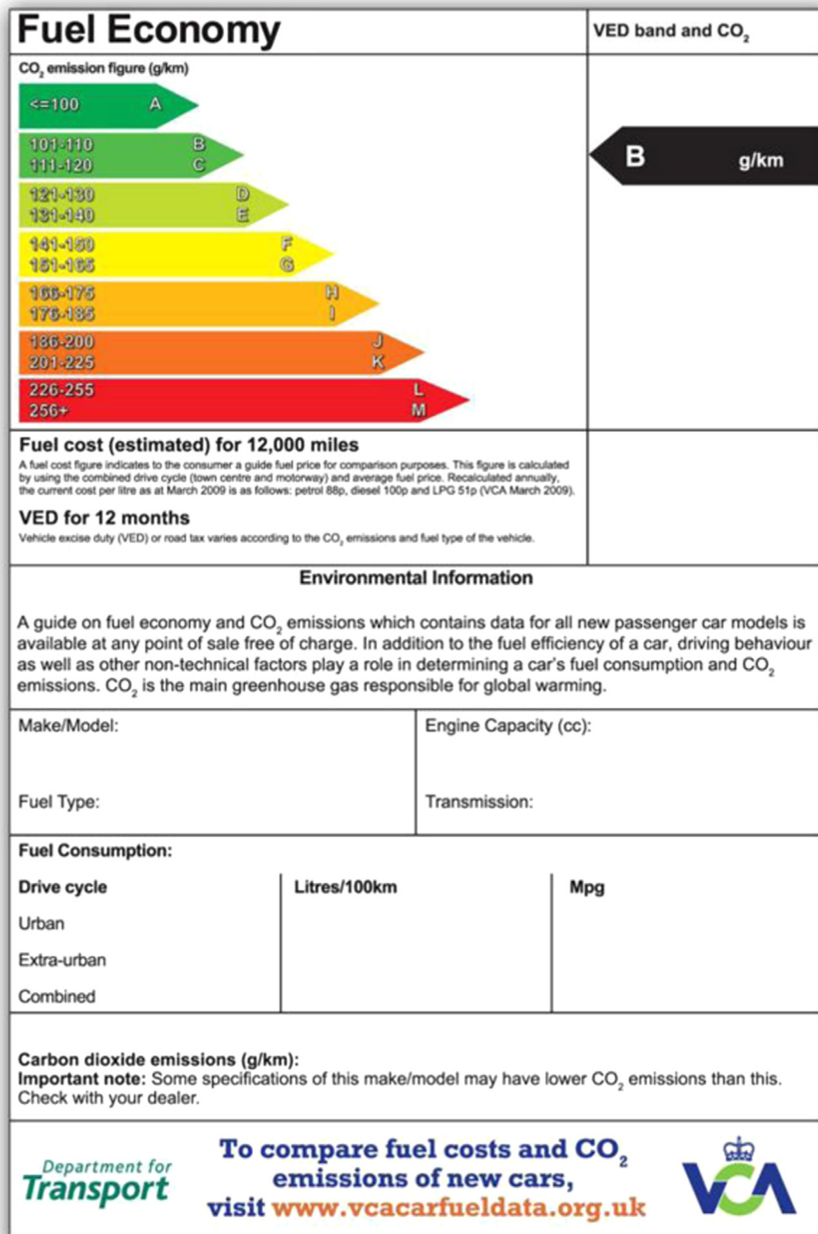

Fig. 1. UK label design.

This paper intends to put into perspective the methods used for environmental rating of vehicles worldwide and how alternative vehicles and its embodied materials are dealt with due to their increasing importance when dealing with increasingly electrified vehicle technologies. Additionally, we expect to contribute to harmonize the way these materials are considered for the rankings by deriving multilinear regression models reliable for alternative vehicle comparisons without needing to know vehicle details, as for instance, vehicle maintenance aspects and exact materials quantity details. The new models purposed are mainly useful for energy and environment agencies/organizations that publish the vehicle rankings for each year's new car sales (e.g.Topten.eu, greenercars.org, ecoscore.be), but can also be used in a website for the use of the car buyer, living in a specific region, by assuming the values for that region by default in the model (the user only has to choose a vehicle model to assess its environmental score).

2. Materials and methods

2.1. Environmental rating methodologies

Vehicle environmental rating methodologies were scrutinized and the following list (Table 1) was found, for several countries. Other documents useful in this matter are the Clean Vehicle Research: LCA and Policy Measures (CLEVER) Report Task 1.2 Overview of environmental vehicle assessments and the recent presentations of the Green Global NCAP Workshop – IEA, Paris, 30th April 2013, published in the IEA website: http://www.iea.org/media/workshops/2013/gfeilabelling/03.1.EUGreenCarRatingsEcolaneApril2013=v2.pdf.

There is still not a unique rating methodology or ranking system for Europe, e.g., Belgium, Germany and United Kingdom have their specific scoring schemes. There are two environmental

Fig. 2. US label for pure electric, hybrid plug-in and fuel cell vehicles.

rating methodologies that use the vehicle material cycle alongside with the fuel cycle for scoring purposes: United States of America ACEEE's Green Book® published in the website http://www.greenercars.org [23] and United Kingdom Green Car Rating published in the website Nextgreencar.com [24], a free-to-use consumer website designed to help car buyers to find, compare and buy greener cars. These will be described in more detail. The limitations encountered in the production and manufacturing impacts among

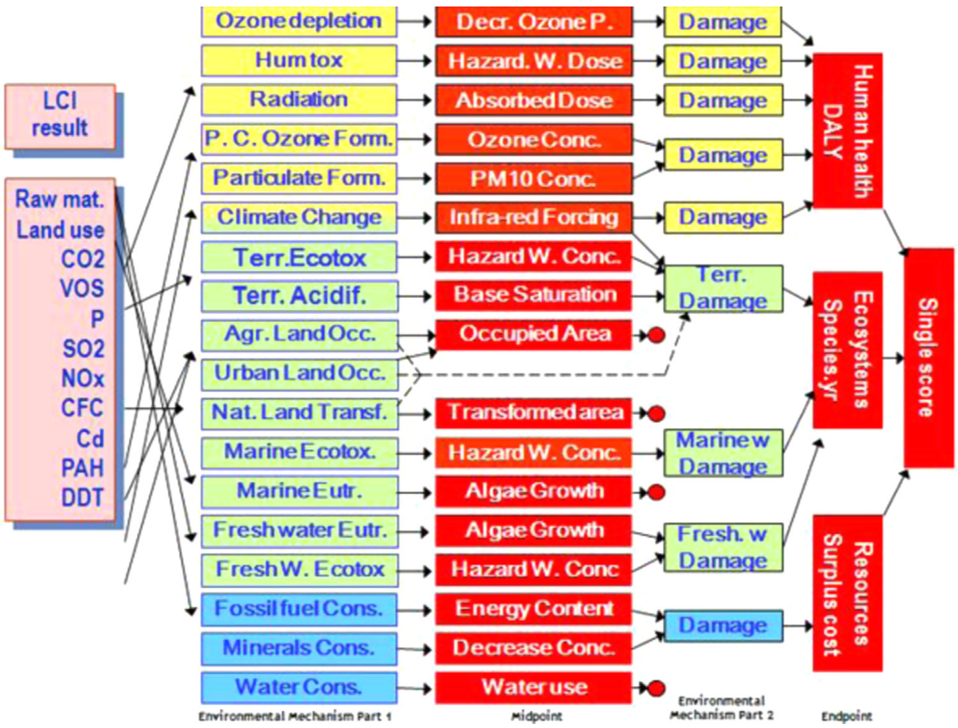

Fig. 3. Eco-Indicator 99 impact categories and single score scheme.

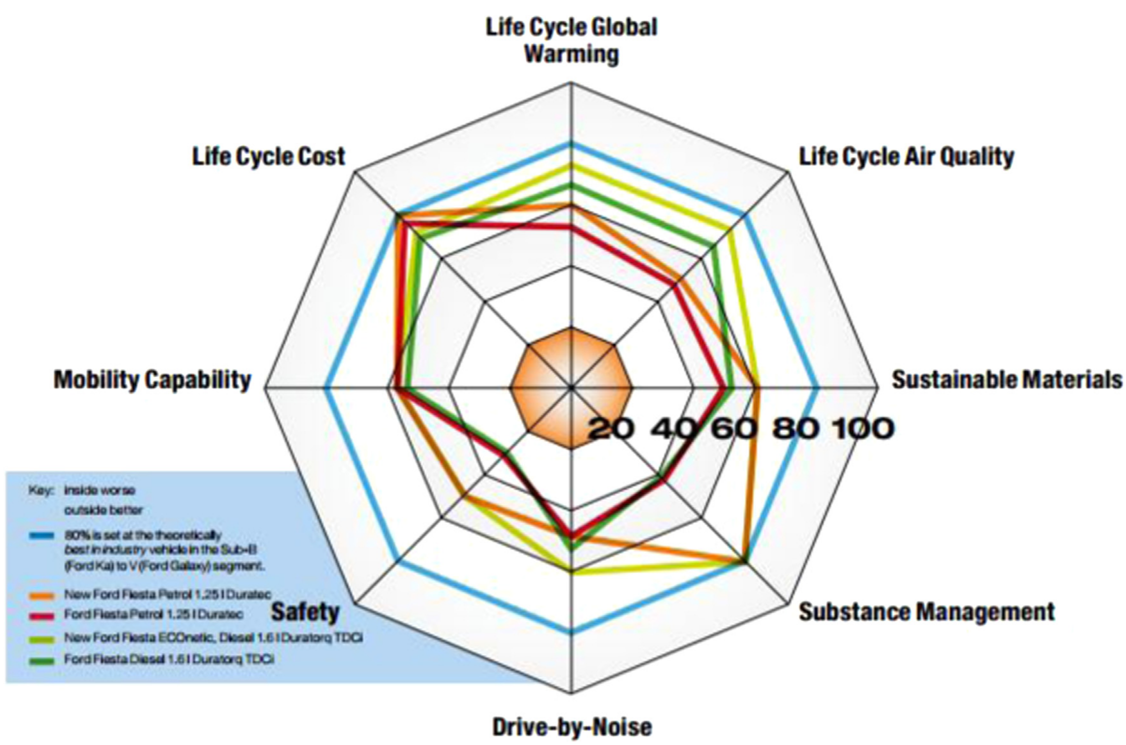

Fig. 4. Product Sustainability Index (PSI) impact categories and spider web scheme.

vehicles having significant different composition or having materials, components and assembly from geographic locations, subject to widely different environmental contexts, are discussed.

2.1.1. *Belgium*

Ecoscore is an environmental score created for the Belgium road vehicles fleet and defined for three vehicle categories: light-duty vehicles, heavy-duty vehicles and two-wheelers. The Ecoscore calculation takes into account the most important pollutants emitted by the vehicle during the driving phase (exhaust emissions, GHG, CO, HC, NO_x, particulate matter (PM) and sulfur dioxide (SO_2)) and emissions from the production and distribution phase of the fuel (fuel cycle emissions, WTT). Emissions from the vehicle assembly and from the production of its components, as well as vehicle maintenance and end-of-life, are not taken into account.

Table 1
List of environmental ranking methodologies and selected characteristics.

Country	Acronyms reference	Emission species	Emission boundaries	Vehicle technologies	Scoring system
United States	Green score	GHG, CO, HC, NO_x, PM, SO_2	Cradle-to-Grave (embodied) Well-to-Wheel (fuel indirect)	ICE, HEV, EV	0–100
Belgium	Ecoscore	GHG, CO, HC, NO_x, PM, SO_2	Well-to-Wheel (fuel indirect)	ICE, HEV, EV	0–100
United Kingdom	Green car rating	GHG, CO, HC, NO_x, PM, SO_2	Cradle-to-Gate (embodied) Well-to-Wheel (fuel indirect)	ICE, HEV, EV	0–100
Germany, Austria, Switzerland	VCD rating	HC, CO, NO_x, PM, CO_2	Tailpipe (fuel in-use)	All	0–10
Mexico	Eco vehicles rating	NO_x, CO_2	Tailpipe (fuel in-use)	All	0–20
Australia	Green vehicle guide	HC, NO_x, PM, GHG	Tailpipe (fuel in-use)	All	1 to 5 stars

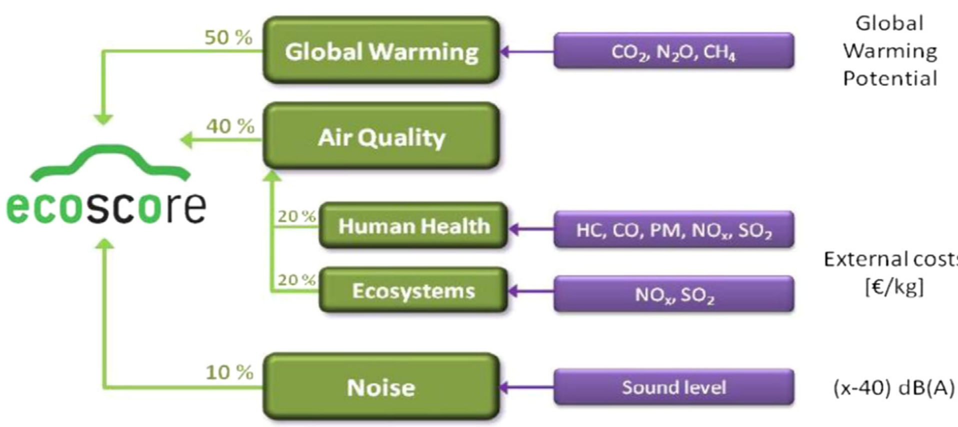

Fig. 5. Ecoscore scheme.

Ecoscore considers the following categories of damages: climate change, air quality depletion (health-impairing effects and effects on ecosystems) and noise pollution. These impact categories are combined through a weighting system to create the Ecoscore Indicator, see Fig. 5 [25].

A total impact (TI) is calculated according to

$$TI = \sum_i \alpha_i q_i \text{ with } \sum_i \alpha_i = 1$$

where α_i is weighting factor of damage category i, as in Fig. 3, and q_i is the normalized damage. Each q_i in category i (global warming, air quality or noise) is calculated using the values for a reference vehicle:

$$q_i = \frac{Q_i}{Q_{i,ref}}$$

where Q_i is total damage of the assessed vehicle in category I, $Q_{i,ref}$ is total damage of the reference vehicle in category i. The reference vehicle is taken to be a Euro 4, with 120 g/km of tailpipe CO_2 and 70 db(A) noise level. The damage Q_i for global warming includes direct tailpipe emissions and indirect fuel upstream emissions.

The final score is given on a higher-is-better scale of zero to 100:

$$EcoScore = 100\ \exp(-0.00357.TI)$$

2.1.2. Germany, Austria, Switzerland (and Topten.eu)

In 1997 the Institut für Energie- und Umweltforschung (German Institute for Energy and Environmental Research) developed a methodology (updated several times since) that is widely used in Europe. It was required by three transport associations (Verkehrsclub Deutschland (VCD) from Germany, Verkehrsclub Österreich from Austria and Verkehrsclub der Schweiz from Switzerland) and by ministry of environment of Berlin. For instance in Germany, Verkehrsclub Deutschland (VCD) publishes every year a magazine that rates vehicles according to their usage impact, and it considers both human health and environmental aspects [26], applying this methodology.

Also several other countries indirectly use this methodology, in a nonofficial level, through an association nominated TOPTEN operating European wide. It rates different domestic appliances and cars. For instance in Portugal, which has no official methodology for vehicle rating, a nonprofit association for environment (Quercus) uses this methodology for conventional drivetrains.

The methodology consists in calculating the total impact through a punctuation system, according to the following weighting parameters: burden caused by pollutants in human health; environmental burden; CO_2 exposure (GHG effect) and burden in human health due to noise. However it considers only in-use emissions.

This methodology attributes different weights to the categories: global warming, noise, air pollution and nature pollution (see Fig. 6).

Final formula for this methodology is the Total Punctuation (TP):

$$TP = GHGimpact \times 0.6 + NI \times 0.2 + HI + NtI$$

where GHG impact is CO_2 punctuation given by $(180 - x) \times 0.0833$, with x given by the CO_2 emissions obtained in NEDC; Noise impact (NI) is db punctuation The scale runs linearly between 10 points for 65 dB(A) and 0 points for 75 dB(A) and more.

Health impact (HI) and nature impact are given by

$$HI = (NO_x \text{ health impact} \times 0.25 + NO_2 \text{ health impact} \times 0.25 + PM \text{ impact} \times 0.5) \times 0.15$$

$$NtI = NO_x \text{ nature impact} \times 0.05$$

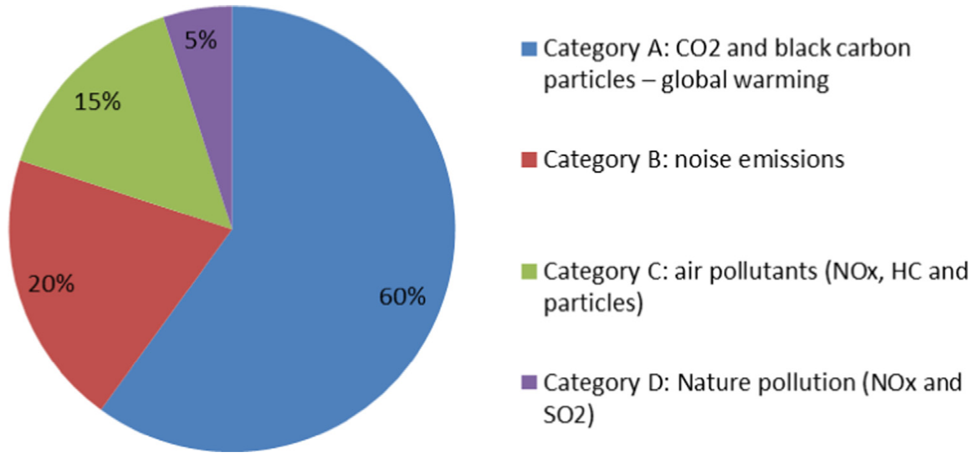

Fig. 6. Weighting of environmental categories in VCD ranking.

2.1.3. Australia

In order for vehicles to be registered for the first time in Australia they must comply with Motor Vehicle Standards Act 1989, which requires vehicles to meet national standards, covering safety and environmental requirements specified in Australian Design Rules (ADR) [23]. These rules specify the maximum allowed emissions that a vehicle must emit in a standard roller bench test, which at the moment reflects international standards, usually referenced as “Euro standards”.

The rating methodology is simple and based on vehicle tailpipe emissions; it assesses air pollution rating and Greenhouse rating relative to HC, NO_x and PM emissions and CO_2, respectively. This methodology sums both ratings and attributes an overall rating based on a combined air pollution and greenhouse score; it also has a classification system that attributes stars regarding the overall rating. Air Pollution Rating is obtained through predefined values according to pollutants emissions standards and GHG rating is obtained from predefined values attributed according to CO_2 emissions measured for vehicle certification (see Tables 2–4).

2.1.4. Mexico eco vehicles rating

The rating is based on Environmental Protection Agency (EPA) vehicle environmental scoring (see Table 5) and focuses mainly on NO_x emission limits for air pollution score and on GHG for CO_2 score. The overall score is the sum of these two 0–10 scores. It covers only in-use tailpipe emissions.

The CO_2 values are estimated based on adjusted fuel economy, meaning the fuel economy measured by the standard test is aggravated by 25%.

2.1.5. US ACEEE's score

Green Book® rating system is based on environmental economics, meaning it attributes a cost to the impact caused by emissions, expressed in an environmental damage index, EDX,

$$EDX = \sum_i Damage(Impact_i)$$

$$EDX = \sum d_{ij} e_{ij}$$

where i is an index over emission species (air pollutants, including greenhouse gases) and j is an index over locations of emissions. d_{ij} is an environmental damage cost (e.g., cents per gram) taken from Delucchi [27]; e_{ij} is the quantity of emissions averaged over a vehicle's operational life (e.g., grams per mile). The damage index so defined represents environmental impacts averaged over vehicle lifetime travel distance and the units can be given in cents per vehicle mile (¢/mi).

To facilitate communication and comparison between vehicles they perform a derivation from the EDX, an indicator to convey rankings in ACEEE's Green Book®, which is the Green Score on a higher-is-better scale of 0–100:

$$\text{Green score} = a \frac{e^{(-EDX)/c}}{(1+(EDX/c))^b}$$

with $a=100$, $b=3$ and $c=8.19$ ¢/mi

Green Score ranges inversely to EDX and it spreads out the scores for future “green vehicles” at the expense of less differentiation among current vehicles. Fig. 7 shows a scheme of the methodology.

For the vehicle in-use stage, the EPA certification emissions are used. The GHG emissions are estimated using the combined fuel consumption on the EPA standard cycles, 45% urban driving (UDDS) and 55% extra-urban driving (HWFET).

For the upstream fuel emissions (Well-to-Tank stage), the values for gasoline and electricity may be found in the report of Delucchi, 2005 [28].

For the materials stage ACEEE's Green Book® considers the pollutants emissions as a linear function of vehicle and battery weight, derived from GREET with the exception of plug-in hybrids and fuel cell, which are not considered within the methodology. For example, Table 6 shows the coefficients for Hybrid-Electric Vehicles (Lithium-ion Batteries) based on GREET software [29], using a lifetime of 120 000 miles.

The CO_2 equivalent emissions are based on the CO_2 Equivalency Factors (CEFs) from the reference [28].

2.1.6. UK's green car rating

United Kingdom Green Car Rating was created in 2006 and is published in the website Nextgreencar.com, a free-to-use consumer website designed to help car buyers find, compare and buy greener cars. It is based on Cleaner Drive Environmental Rating Tool 2004 and extended to include vehicle production emissions (estimated). It includes CO_2 and all regulated emissions as measured by NEDC and published in the Vehicle Certification Agency (for tailpipe emissions). The total impact is the sum of total air quality impact with the total GHG impact. Two additional scores are given: the air quality score and the GHG score. In Fig. 8 scheme for UK cleaner drive rating is presented.

The air quality (AQ) impact is based on CO, HC, NO_x, PM and SO_2. External costs are based on ExternE [30]. Fuel cycle emissions are based on MEET report [31]. The total impact and score for AQ are calculated according to tailpipe, fuel cycle and embodied air pollutant emissions multiplied by the respective external cost in €/km. The GHG

Table 2
Air pollution ratings incorporating Euro 5 and Euro 6 (applicable from 2006), for Australia rating scheme.

Air pollution rating	Fuel type	Vehicle type[a] RM=reference mass[b] (kg)	ADR compliance	Additional GVG emissions requirements	Equivalent Euro Standard	HC limit (g/km)	NO_x limit (g/km)	PM[e] limit (g/km)
10	Electric	All	All	–	–	–	–	–
8.5	Petrol, LPG, NG	All	ADR79/02	Euro 4 certification (minimum) and HC ≤ 0.035 g/km and $NO_x \le 0.028$ g/km[c]	Beyond Euro 6	0.035	0.028	–
8.5	Diesel	All	ADR79/02	Euro 4 certification (minimum) and HC ≤ 0.035 g/km and $NO_x \le 0.028$ g/km and PM10 ≤ 0.00875 g/km[d]	Beyond Euro 6	0.035	0.028	0.00875
7.5	Petrol, LPG, NG	Passenger Goods carrying (RM $\le$ 1305)	ADR79/02	Euro 5 or 6 certification	Euro 5 or 6	0.1	0.06	0.005
7.5	Diesel	Passenger Goods carrying (RM $\le$ 1305)	ADR79/02	Euro 6 certification	Euro 6	– 0.08 $HC+NO_x$ ≤ 0.17		0.005
6.5	Petrol, LPG, NG	Goods carrying (RM $\le$ 1305)	ADR79/02	Euro 4 certification	Euro 4	0.1	0.08	–
6.5	Petrol, LPG, NG	Goods carrying (1305 < RM $\le$ 1760)	ADR79/02	Euro 5 or 6 certification	Euro 5 or 6	0.13	0.075	0.005
6.5	Diesel	Goods carrying (1305 < RM $\le$ 1760)	ADR79/02	Euro 6 certification	Euro 6	– 0.105 $HC+NO_x$ ≤ 0.195		0.005
6	Petrol, LPG, NG	Goods carrying (RM > 1760)	ADR79/02	Euro 5 or 6 certification	Euro 5 or 6	0.16	0.082	0.005
6	Diesel	Goods carrying (RM > 1760)	ADR79/02	Euro 6 certification	Euro 6	– 0.125 $HC+NO_x$ ≤ 0.195		0.005
6	Diesel	Passenger Goods carrying (RM $\le$ 1305)	ADR79/02	Euro 5 certification	Euro 5	– 0.18 $HC+NO_x$ ≤ 0.23 $HC+NO_x \le 0.195$		0.005
5.5	Petrol, LPG, NG	Goods carrying (RM > 1760)	ADR79/02	Euro 4 certification	Euro 4	0.16	0.11	–
5.5	Diesel	Goods carrying (1305 < RM $\le$ 1760)	ADR79/02	Euro 5 certification	Euro 5	– 0.235 $HC+NO_x$ ≤ 0.295		0.005
5	Petrol, LPG, NG	Goods carrying (RM $\le$ 1305)	ADR79/01	–	Euro 3	0.2	0.15	–
5	Diesel	Goods carrying (RM > 1760)	ADR79/02	Euro 5 certification	Euro 5	0.28 $HC+NO_x$ ≤ 0.35		0.005
5	Diesel	Passenger goods carrying (RM $\le$ 1305)	ADR79/02	–	Euro 4	0.25 $HC+NO_x$ ≤ 0.30		0.025
4.5	Petrol	Goods carrying (1305 < RM $\le$ 1760)	ADR79/01	–	Euro 3	0.25	0.18	–
4	Petrol, LPG, NG	Goods carrying (RM > 1760)	ADR79/01	–	Euro 3	0.29	0.21	–
4	Diesel	Goods carrying (1305 < RM $\le$ 1760)	ADR79/02	Euro 4 certification	Euro 4	0.33 $HC+NO_x$ ≤ 0.39		0.04
3	Diesel	Goods carrying (RM > 1760)	ADR79/02	Euro 4 certification	Euro 4	0.39 $HC+NO_x$ ≤ 0.46		0.06
2.5	Diesel	Passenger Goods carrying (RM $\le$ 1305)	ADR79/00	Euro 3 certification	Euro 3	0.50 $HC+NO_x$ ≤ 0.56		0.05
2	Diesel	Goods carrying (1305 < RM $\le$ 1760)	ADR79/00	Euro 3 certification	Euro 3	0.65 $HC+NO_x$ ≤ 0.72		0.07
2	Diesel	Passenger goods carrying (RM $\le$ 1250)	ADR79/00	–	Euro 2	$HC+NO_x \le 0.70$		0.08

Table 2 (*continued*)

Air pollution rating	Fuel type	Vehicle type[a] RM=reference mass[b] (kg)	ADR compliance	Additional GVG emissions requirements	Equivalent Euro Standard	HC limit (g/km)	NO_x limit (g/km)	PM[e] limit (g/km)
1.5	Diesel	Goods carrying (RM > 1760)	ADR79/00	Euro 3 certification	Euro 3	0.78; $HC+NO_x \leq 0.86$		0.10
1	Diesel	Goods carrying (1250 < RM ≤ 1700)	ADR79/00	–	Euro 2	$HC+NO_x \leq 1.00$		0.12
0.5	Diesel	Goods vehicles (RM > 1700)	ADR79/00	–	Euro 2	$HC+NO_x \leq 1.20$		0.17

The Euro 5 and Euro 6 emission limits for petrol vehicles are the same. The Euro 6 HC and NO_x emission limits for diesel vehicles are more stringent than Euro 5. (The PM limits are the same).

[a] Passenger vehicles with a maximum mass greater than 2500 kg and, in the case of ADR79/00, vehicles with greater than 6 seats are, for the purposes of the emissions standards, treated as goods carrying vehicles. The maximum mass of a vehicle refers to the maximum laden mass that is technically possible for that vehicle.

[b] The reference mass of a vehicle refers to the unladen vehicle mass plus 100 kg.

[c] These HC and NO_x values represent 35% of the Euro 4 limits for a standard petrol passenger car.

[d] These HC and NO_x limits are the same as per (c) above and the PM value is equivalent to 35% of the Euro 4 limit for a standard diesel passenger car.

[e] the Euro 5 and Euro 6 particulate (PM) limit of 0.005 applies to all diesel vehicles, and petrol vehicles with direct injection technology only.

Table 3
GHG rating in Australia environmental rating scheme.

Greenhouse rating	CO_2 Emissions (combined g/km)	Greenhouse rating	CO_2 Emissions (combined g/km)
10	≤ 60	5	241–260
9.5	61–80	4.5	261–280
9	81–100	4	281–300
8.5	101–120	3.5	301–320
8	121–140	3	321–340
7.5	141–160	2.5	341–360
7	161–180	2	361–380
6.5	181–200	1.5	381–400
6	201–220	1	401–420
5.5	221–240	0.5	421–440

Table 4
Overall rating in Australia environmental rating scheme.

Overall rating	**Combined air pollution & greenhouse score**
5 Stars	Combined score ≥ 16
4.5 Stars	15 ≤ combined score < 16
4	14 ≤ combined score < 15
3.5	11.5 ≤ combined score < 14
3	9.5 ≤ combined score < 11.5
2.5	8 ≤ combined score < 9.5
2	6.5 ≤ combined score < 8
1.5	5 ≤ combined score < 6.5
1	Combined score < 5

score is similar to the AQ Score but considers CO_2, CH_4 and N_2O.

$$Q_{AQ}(\text{total}) = Q_{AQ}(\text{tailpipe}) + Q_{AQ}(\text{fuel cycle}) + Q_{AQ}(\text{embodied}) \text{ and}$$

$$Q_{AQ} = \Sigma_i p_i c_i$$

$$AQ \text{ score} = 100\text{–}100 \times Q_{AQ}(\text{total})/Q_{AQ}(\text{max emission total})$$

where Q_{AQ} is the AQ External Cost in €/km; p_i=emission of pollutant i in g/km; c_i=external cost of emission of pollutant i in €/g. Q_{AQ} (max emission total)=total AQ external cost for the max emission limits in €/km.

UK proportion of urban to rural kilometers for passenger cars is 46%/54%, meaning this weighting is used for average external costs per pollutant at the tailpipe stage. Rural external cost factors are used to calculate the cost of fuel cycle AQ emissions to reflect the fact that the majority of these emissions occur away from urban areas.

The overall score is

$$\text{Overall score} = 100\text{–}100 \times Q_{\text{Overall}}(\text{total})/Q_{\text{Overall}}(\text{max emission total})$$

where Q_{Overall} (total) is the total overall environmental external cost in €/km; Q_{AQ} (total) is the total AQ criteria external cost in €/km; Q_{GHG} (total) is the total GHG criteria external cost in €/km; Q_{Overall} (max emission total) is the total external cost for the air quality and GHG max emission limits in €/km.

Vehicle cycle embodied emissions regard components production, assembling and materials cradle-to-gate (CTG), where no end-of-life is accounted, claiming the distribution and disposal represent less than 1% of the overall embodied material life cycle. The data required by the model to estimate the emissions associated with the vehicle cycle are the mass of the vehicle (kg), the distribution of the material used in the vehicle by mass (kg) using a system of 12 material category types, according to the Green Car Rating methodology [24]. The values per km are estimated using

Table 5
Similarities between US EPA vehicle environmental scoring and Mexican system.

US EPA – Vehicle environmental scoring GHG score MY 2011 & MY 2012

Score	**gCO_2/mile**	**Gasoline (minimum combined mpg)**	**Diesel (minimum combined mpg)**	**E85 (minimum combined mpg)**	**Natural gas (minimum combined mpg)**
10	< 188	48	55	35	39
9	188–233	39	44	28	32
8	234–279	33	37	23	26
7	280–325	28	32	20	23
6	326–371	25	28	18	20
5	372–417	22	25	16	18
4	418–463	20	22	14	16
3	464–509	18	20	13	14
2	510–555	17	19	12	13
1	> 555	1	1	1	1

Mexican system for GHG score

Score	gCO_2/km	Gasoline (km/l)	Diesel (km/l)
10	0–126.86	> 18.7	> 21.26
9	126.86–155.05	15.5–18.7	17.43–21.26
8	155.05–183.24	12.75–15.30	14.88–17.43
7	183.24–211.44	11.05–12.75	12.75–14.88
6	211.44–239.63	9.78–11.05	11.48–12.75
5	239.63–267.82	8.93–9.78	10.20–11.48
4	267.82–296.01	8.08–8.93	9.35–10.20
3	296.01–324.20	7.23–8.08	8.50–9.35
2	324.20–352.39	6.80–7.23	7.65–8.50
1	352.39–380.58	6.38–6.80	7.23–7.65
0	> 380.58	< 6.38	< 7.23

US EPA-vehicle environmental scoring air pollution score MY 2011 & MY 2012

Score	US EPA Tier 2 emission standard	California air resources board LEV II Emissions standard
10	Bin 1	ZEV
9	xx	PZEV
8	Bin 2	SULEV II
7	Bin 3	xx
6	Bin 4	ULEV II
5	Bin 5	LEV II
4	Bin 6	LEV 2 opt.1
3	Bin 7	xx
2	Bin 8	SULEV II lg trucks
1	xx	ULEV & LEV lg trucks

Mexican system for air pollution

Score	US EPA Tier 2 emission standard	Maximum allowable NO_x (g/1000 km)
10	Bin 1	0
9	Bin 2	0–12.43
8	Bin 3	12.43–18.65
7	Bin 4	18.65–24.86
6	Bin 5	24.86–43.51
5	Bin 6	43.51–62.15
4	Bin 7	62.15–93.23
3	Bin 8	93.23–124.3
2	Bin 9	124.3–186.45
1	Bin 10	186.45–372.9
0	Bin 11	372.9–559.35

Tables 7 and 8 and assuming a vehicle lifetime in km. Again rural external cost is applied.

No entry denotes that no data is available and the model therefore assumes no emissions of this type.

2.2. Embodied emissions model proposal

The tailpipe-based scoring methodologies are less dubious since they rely on values measured on standard driving cycles, and are always updated. The scoring methodologies that consider upstream emissions from the fuel and from the materials introduce more uncertainties in the data and respective score calculation. Usually fuel/materials life cycle, data is dated and should be updated to better reflect the current case studies. However, they allow to differentiate a fuel cell and an electric vehicle, both with equal and best scores in tailpipe-based rating schemes. The advantage in Cradle-to-Grave/Cradle-to-Gate versus Well-to-Wheel boundary studies is it allows a higher degree of environmental distinction between conventional and electrified technologies. The limitations encountered in the production and manufacturing impacts among

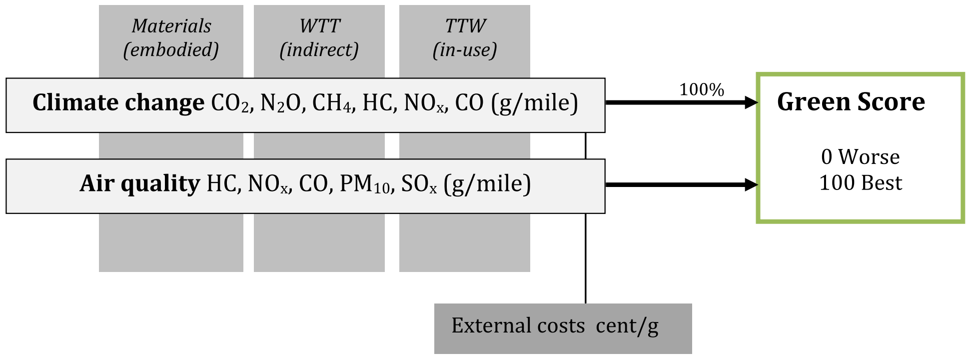

Fig. 7. Scheme for US Green score rating.

Table 6
Embodied material emissions for HEV.

Emissions	Weight Coefficient (grams per lb of vehicle)	Battery weight coefficient (grams per lb of battery)
NO_x	2.83	6.38
PM_{10}	3.47	6.79
SO_x	7.59	44.93
CO	12.42	– 10.06
GHG	2084	5421

vehicles having significant different composition, or having materials components and assembly from geographic locations subject to widely different environmental contexts, are discussed. In addition, using aggregate data with simplifications usually introduces uncertainty in the results. Bearing in mind these difficulties, but aiming at simplifying the environmental rating scores, an attempt is made to derive regression models multicountry-wide.

Multiple linear regression attempts to model the relationship between two or more explanatory variables and a response variable by fitting a linear equation to the observed data. Every value of the independent variables is associated with a value of the dependent variable *y*. Multiple Linear Regression models were developed using Intercooled Stata 9 software. It is important to stress that the developed models are only for environmental rating purposes and if a more detailed embodied materials life-cycle study is the objective then the original GREET/Simapro model should be used, or a careful LCA study following ISO 14040 principles should be developed.

In order to have a significant number of simulations for each technology the GREET model was run 22,000 times, and the Input and Output variables values were collected and finally stored in an Excel sheet. About 90% of the data was used for model construction purposes and the remaining for independent validation. This means that 10% of the runs were used to compare with the regression data obtained for the other 90%.

After producing the sample, a multiple linear regression method was used, having the Input variables (e.g. vehicle mass, see Table 9) as independent variables and the Output variables (e.g. CO emissions see Table 9) as dependent variables.

Due to its simplicity the Least Linear Squares method [32] was applied to the sample returning coefficients for each independent variable, meaning that each technology and each Output variable is related to a specific group of coefficients, which leads to 40 different equations (models) presented in Appendix A. The coefficients obtained were subsequently subjected to statistical analysis to verify their statistical significance. To this end, a *t* Student hypothesis [32] test was used to accept or reject the null hypothesis (coefficient significant) of the estimated coefficients being significant, depending on the value of the resulting *t*. Thus, for a confidence level of 95%, if *t* value, in modulus, is greater than 2.96, then the coefficient is significant and should be considered [32]. Otherwise, it is void and should be disregarded.

Since the independent variables were found to present some non-linearity between them, it was decided to apply first the (neperian) logarithm function to the dependent variables. Then an exponential function was applied to ensure the positivity of all estimated values that are essential, since in the lifecycle of materials there is always energy consumption and emissions. The final models are given generically by

$$Y = \exp(c_1x_1 + c_2x_2 + c_3x_3 + \cdots + c_nx_n)$$

where Y is a dependent variable, x_n the independent variable and c_n its coefficient.

Input and output variables are presented in Table 9. Input ranges were as presented in Table 10. In these simulations the maintenance of the vehicle was included and the intervals of components replacement are as shown in Table 11. This is especially relevant to couples with vehicle lifetime and to know the number of each item/component replacements.

It is of note that this initial process was not designed to simulate real vehicles, but to cover all possible variations in the composition of the vehicle, per technology, within the universe of each parameter input (Table 10).

Note that these models are constrained to use under certain conditions that are related to the inputs range and type of battery used (Table 9), the maintenance periods assumed for each component and for conventional material-based vehicles. Also, GREET, just like any other software, has many built-in assumptions and equations.

2.2.1. *Validation*

The regression models were validated against Volkswagen life cycle assessments (LCAs), The Golf Environmental Commendation – Background Report, for the conventional ICEV Golf VII 1.2 l TSI [63 kW] and Golf VII 1.6 l TDI [77 kW]. In this study the inventory for the manufacturing is 5 t CO_2 for both, and the end-of-life is negligible.

The Nissan Leaf data taken from Hawkins et al. [16] is also used to compare with the simplified methodologies. In this study, assuming 150,000 km they estimate the GWP from BEV production to be 87–95 g carbon dioxide equivalent per kilometer (g CO_2-eq/km), which is roughly twice the 43 g CO_2-eq/km associated with ICEV production. Battery production contributes 35–41% of the BEV production phase GWP, whereas the electric engine contributes 7–8%.

For the Toyota Prius plug-in data, the study [33] was used to compare the production phase of a PHEV30 with a conventional vehicle. In this study 240,000 km are assumed for the vehicle

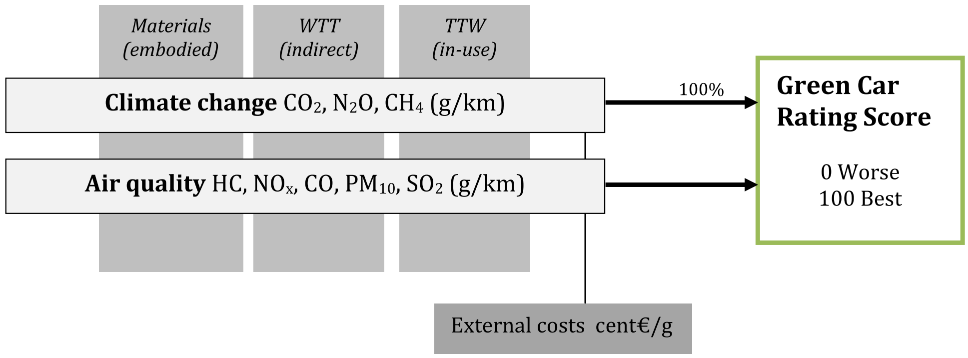

Fig. 8. Scheme for UK cleaner drive rating.

Table 7
Breakdown of the materials for different vehicle technologies (in %).

	ICE Petrol	ICE Diesel	HEV Petrol-NiMH	ICE bi-fuel	Conversion BEV Lead-acid	Dedicated BEV Lead-acid
Ferrous	59.9	61.1	59.8	62	47.6	34
Composites	0	0	0	0	0	1.8
Aluminum	4.9	4.2	12.9	4.6	1.2	3.4
Copper	0.3	0.4	3.2	0.3	1	5.5
Zinc	0.3	0.4	0.3	0.3	0.6	0
Lead	0.9	1.1	0.5	0.8	15.4	28.3
Magnesium	0.3	0.4	0.9	0.3	0.6	0
Nickel	0	0	0.9	0	0	0
Plastics	15.8	15.4	11.9	15	14	10.8
Fluids	6	6.1	2.7	5.7	2.7	8.9
Rubbers	4.2	4.3	3.1	3.9	3.7	3.1
Glass	2.8	2.5	2.7	2.7	2.5	3.1
Others	4.6	4.1	1.1	4.4	10.7	1.1
Total	100	100	100	100	100	100

Table 8
Emissions due to materials production.

g/kg	PM	NO_x	CO	HC	SO_2	CO_2	CH_4	N_2O
Ferrous	1.85	3.33	29.02	1.4	3.77	2352	1.23	0.12
Composited		36		12	23	12000	12	
Aluminum	8.25	12	1.65	15.45	33.15	6049 *		
Copper		10		1.4	658	20000	1.4	
Zinc		20		9.7	65	10000	9.7	
Lead		2.6	0.34	0.16	7.4	1680	0.06	
Magnesium		20		9.7	65	10000	9.7	
Nickel		10		1.4	658	20,000	1.4	
Plastics		20.7		19	26.7	3800	19	
Rubbers		10		5	15	1700	5	
Glass		2.3		0.79	2.3	760	0.79	

* CO_2 Equivalent (includes all greenhouse gas emissions).

lifetime, a value of 120 kg CO_2 eq/kWh of battery capacity and a value of 8500 kg CO_2 eq/vehicle.

Fig. 9 shows how conventional official LCA GHG category compares against other studies and, in particular, with the proposed multicountry regression model. The ACEEE's Green Score and UK Green Car embodied material assessment methodologies are also marked in the graphs for the discussion.

Despite the specificities of each study in terms of assumptions, scope and GHG equivalency factors the trends for comparing new technologies with conventional ones are kept. This means that at least the differences between technologies are qualitatively similar, which is what really matters for the environmental ranking systems, which ranks the vehicles, and not so much the absolute value per se. Nevertheless, developing better methods for rating vehicles according to environment impacts from materials and parts production, assembly, and disposal remains an area for future improvements.

2.3. *Environmental rating methodologies application*

We consider the following five different vehicle technologies, sold worldwide, and real vehicle characteristics (see Table 12) for application of the reviewed methodologies and developed regression models: Internal Combustion Engine Vehicle Volkswagen Golf 1.2 TSI (ICEV), Hybrid Electric Vehicle Toyota Prius (HEV), Plug-in Hybrid Electric Vehicle Toyota Prius Plug-In (PHEV), Battery Electric

Table 9
Analyzed input/output data.

Input	Output
• Mass of the vehicle, kg • Mass of the propulsion battery[a], kg • Lifetime of the vehicle, km • Power of fuel cell[b], kW • Electricity production mix[c] (%) • Fractions of recycled materials[d] (%)	• Energy consumption, kJ/km • GHGs emission, (CO_2, N_2O, CH_4)[e] g/km • Pollutant emissions (CO, VOC, NO_x, SO_x, PM_{10} and $PM_{2.5}$), g /km

[a] In the case of the HEV, PHEV, BEV and FCHEV.
[b] In FCHEV's case.
[c] Energy sources used: oil (%), natural gas (%), coal (%), nuclear (%), biomass (%), renewables (%).
[d] Fractions of recycled materials used: steel (%), wrought aluminum (%), cast aluminum (%) nickel (%), lead (%).
[e] GWP factor: (CO_2)=1; (N_2O)=25; (CH_4)=298.

Table 10
Simulation ranges for each vehicle.

Variable	Technology	Minimum value	Maximum value
Vehicle mass, kg	All	750[a]	2750
Lifetime, km	All	100,000	300,000
Electricity generation *Mix*, %	All	0	100
Recycled materials %	All	0	100
Propulsion battery mass, kg	HEV	20	80
	PHEV	80	240
	BEV	100	500
	FCHEV	13	153
Fuel Cell power, kW	FCHEV	70	110

[a] Minimum value of mass for fuel cell hybrid vehicle considered was 1250 kg due to heavy components use, e.g. fuel cell and tank.

Table 11
Intervals of components replacement – vehicle maintenance.

Components		Replacement range (km)
Tires		65,000
Batteries	Pb–Ac	75,000
	Li-ion and NiMH	160,000
Fluids	Motor oil	15,000
	Brake and powertrain cooling fluids	65,000
	Transmission fluid	260,000
	Windshield liquid	12,000

Vehicle Nissan Leaf (BEV) and Fuel Cell Hybrid Electric Vehicle Honda FCX Clarity (FCHEV). As Green Book® methodology does not have the specific coefficients to calculate the PHEV embodied emissions, this vehicle can be treated as a HEV because data are similar, and they both have lithium-ion batteries. The major error that could accrue from this assumption, due to the batteries' weight difference between PHEV and HEV, is considered irrelevant due to the coefficients multiplication by the respective weight. Fuel cell technology is not possible to simulate with the reviewed methodologies but was included in the developed one, to see whether this technology would rank on top or not of the others.

3. Results

The results section focuses on the application of reviewed methodologies to the vehicle technologies of Section 2.3 and on the purposed embodied material model validation. Table 13 presents the results from the original external costs (converted to the same monetary units and to the same units of distance), scores and rankings for US and UK methodologies.

These rankings reveal that pure electric and plug-in hybrid occupy the higher ranks, which is consistent with previous works based on detailed LCA, for example, [8,10,11].

Regarding hybrid and diesel technologies, they rank very similar, in the intermediate positions, which is also consistent with, for example, [11]. Conventional gasoline occupies a worser position compared to alternative technologies, which is consistent with the literature studies that include fuel cycle and embodied emissions cycle [8–13,21].

The developed models were used to estimate embodied emissions of vehicles in Table 12 and therefore to estimate their final scores in the ACEEE's Green Book® and in UK's Green Car rating methodology. Fig. 10 shows the application of the proposed embodied emission models (see Appendix A) to both methodologies and are compared to each other. As it can be seen, results show that vehicle rankings are not affected by the use of the proposed embodied materials model, which may indicate its potential. The advantage of the developed correlations is the potential to be applied in different regions/countries knowing only public accessible specifications and covering several electric vehicle typologies including fuel cells, which might be helpful for environment agencies/organizations that publish the vehicle rankings for each year's new car sales (e.g.Topten.eu, greenercars.org, ecoscore.be). Note that for Fuel Cell vehicle there is no data from Green Book® or UK's methodology. For PHEV, HEV data was used. Although this data is not considered in the reviewed

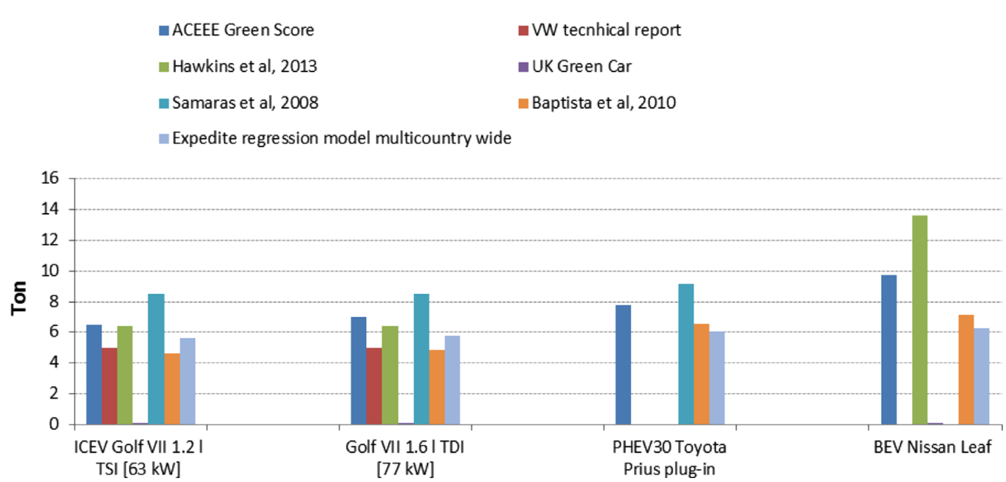

Fig. 9. Comparison of several studies' embodied GHG emissions regarding vehicle manufacturing.

Table 12
Real vehicle characteristics.

	Technology	Fuel	ICE power (kW)	Elec. motor (kW)	Weight (kg)	Battery weight (kg)	Battery
ICEVDiesel-VW Golf (2.0 TDI Bluemotion)	ICEV	Diesel	103[a]	–	1366 [a]	17.3	–
ICEVPetrol-VW Beetle (2.0 TSI 200PS M6)	ICEV	Petrol	147[a]	–	1439[a]	17.3	–
HEV-Toyota Prius (1.8)	Hybrid	Petrol	100[b]	60[b]	1500[b]	22.1 + 50[b]	Ni-MH
BEV-Nissan Leaf	Electric	Electricity	–	80[c]	1525[c]	22.1 + 235.3[c]	Li-Ion
PHEV-Toyota Prius Plug-in (1.8)	Hybrid Plug in	Petrol + Electricity	100[d]	60[e]	1525[e]	22.1 + 59.5[e]	Li-Ion
FCHEV-Honda FCX clarity	Fuel Cell Vehicle	Compressed Hydrogen Gas	–	100[f]	1625[f]	22.1 + 16.7[f]	Li-Ion

[a] (www.carfolio.com, 2012).
[b] (www.toyota-tech.eu, 2012).
[c] (www.nissan.pt, 20112).
[d] (www.toyota.pt, 2012).
[e] (www.toyota.com, 2012).
[f] (http://automobiles.honda.com, 2012).

Table 13
External costs results for overall life cycle and respective scores and rankings for the technologies analyzed.

Country	Air quality external cost (cent€/km)	GHG external cost (cent €/km)	Overall external cost (cent€/km)	Score	Ranking
US	0.22	0.31	**0.54**	57.23	**1st Nissan Leaf (BEV)**
	0.23	0.31	**0.54**	57.05	**2nd Toyota Prius Plug-in (PHEV)**
	0.25	0.33	**0.58**	54.79	**3rd Toyota Prius (HEV)**
	0.20	0.43	**0.63**	52.32	**4th VW Golf (ICEVDiesel)**
	0.26	0.60	**0.86**	42.02	**5th VW Beetle (ICEVPetrol)**
UK	0.12	0.03	**0.15**	84.06	**1st Nissan Leaf (BEV)**
	0.12	0.07	**0.19**	79.93	**2nd Toyota Prius Plug-in (PHEV)**
	0.18	0.12	**0.29**	69.65	**3th VW Golf (ICEVDiesel)**
	0.21	0.09	**0.30**	68.96	**4rd Toyota Prius (HEV)**
	0.35	0.17	**0.52**	45.71	**5th VW Beetle (ICEVPetrol)**

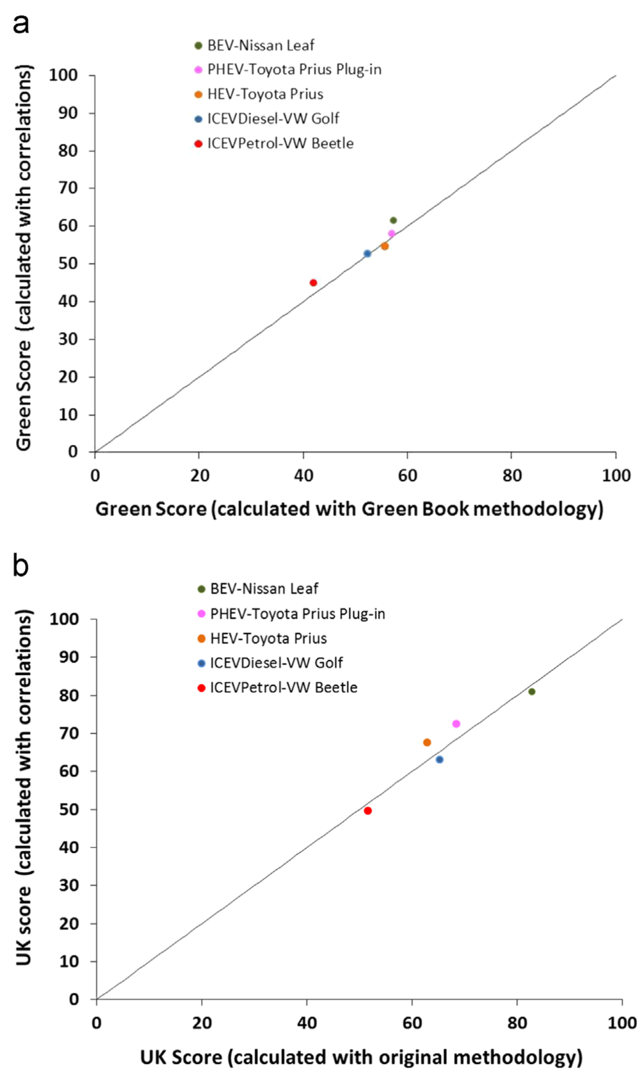

Fig. 10. Original versus proposed model rankings (a) US, (b) UK.

methodologies, by using the proposed models the FCHEV Honda FCX Clarity will rank on top, which is also consistent with literature data.

Fig. 10 shows the original rankings compared with those obtained using the proposed models.

The use of the proposed correlations does not compromise original vehicle rankings, despite the absolute values being different, especially in the case of the UK, where the embodied contribution to overall air quality and GHG ranking is higher per km.

The main advantage of the proposed methodology is to cover production and maintenance throughout vehicle life, and to consider plug-in and fuel cell vehicle technologies. It could be used for other regions' application such as China and Japan.

4. Discussion

The contribution of up to 17% for total LCA GHG emissions ([8–13]), especially for electrified vehicle technologies, shows that it is relevant to consider embodied material emissions in environmental rankings of light-duty vehicles. The differences between methodologies reviewed and purposed are pointed out in the following scheme (Fig. 11).

Despite being consistent so far with LCA studies, embodied models should be subjected to future developments, and special attention should focus on the uncertainties associated with the chosen inputs, for example, in the simplifications of considering one electricity mix for the production of all vehicle components: car is manufactured at a single site, which may be true for the final

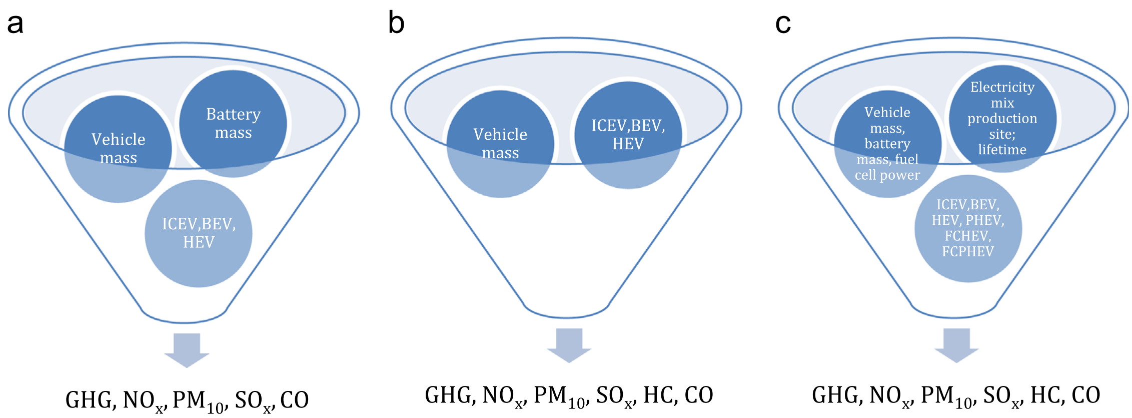

Fig. 11. Scheme for the main input data differences for the embodied emissions models in each environmental ranking methodology. (a) US, (b) UK, and (c) multicountry proposed model.

assembly, but hardly for all of the thousands of components going into the vehicle.

5. Conclusions and policy implications

This paper reviews environmental ranking methodologies that are used to compare light-duty vehicles. Focus is on the ones that consider vehicle embodied material emissions due to its relevance in electrified vehicle technologies. The application of existing methodologies to BEV, PHEV, HEV, ICEV diesel and ICEV gasoline technologies reveals rankings consistent with LCA-based literature data (BEV and PHEV leading the rankings, HEV and ICEV Diesel occupying intermediate ones, and gasoline ICEV being in the last position).

The assessment of materials life cycle of vehicles for ranking purposes is considered in US and UK environmental scoring methodologies. US rating methodology uses linear correlations with vehicle and battery weight based on the GREET software. UK's deal with the percentages of main automotive materials (ferrous, composites, aluminum, copper, zinc, lead, magnesium, nickel, plastics, rubber, glass, others) and respective weights. An attempt to derive multicountry regression models based on publicly available info was made, as a function of vehicle mass, battery mass, fuel cell power, electricity mix of production site and vehicle lifetime, to cope with existing alternative vehicle technologies and multicountry specificities. The idea was avoiding a detailed knowledge of extensive databases concerning vehicle materials requiring each specific material used in each propulsion component and vehicle body. The main target users are agencies/organizations that publish the vehicle rankings for each year's new car sales (e.g.Topten.eu, greenercars.org, ecoscore.be). The developed model proved its suitability for environmental rating purposes. However, embodied material life cycle models should be subjected to future developments, and special attention should focus on the uncertainties associated with the chosen inputs, for example, in the simplifications of considering one electricity mix for the production of all vehicle components and for its assembly. Electronics and traction battery production are likely to drive certain impacts that are located in Asia, for example. Despite these future improvements, it is essential to find ways to communicate the holistic environmental ratings to consumers to foster a market for vehicles with reduced environmental burdens, which will be crucial for progress toward an environmentally sustainable transportation system.

Acknowledgments

Thanks are due to Fundação para a Ciência e Tecnologia FCT for the PhD financial support (SFRH/BD/73416/2010). Authors would like to acknowledge MIT Portugal Program and FCT – Fundação para a Ciencia e Tecnologia (National Science and Technology Foundation) through the Project "Assessment and development of integrated systems for electric vehicles" (MIT-Pt/EDAM SMS/0030/2008).

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2014.05.055.

References

[1] WEC. Global transport scenarios 2050. World Energy Council; 2012.
[2] Silva C. At what extent the benefits of introducing alternative light-duty vehicles offset those of increasing the buses average occupancy? Energy Convers Manag 2013;70:211–9.
[3] Baptista PC, Silva CM, Peças Lopes JA, Soares FJ, Almeida PR. Evaluation of the benefits of the introduction of electricity powered vehicles in an island. Energy Convers Manag 2013;76:541–53.
[4] Baptista PC, Silva CM, Farias TL, Heywood JB. Energy and environmental impacts of alternative pathways for the Portuguese road transportation sector. Energy Policy 2012;51(0):802–15.
[5] EC. Directive 1999/94/EC European Comission Official Journal; 2000.
[6] EPA. New fuel economy and environmental labels for a new generation of vehicles, edited by Office of Transportation and Air Quality: Environmental Protection Agency; 2011.
[7] Mahlia TMI, Tohnoc S, Tezukac T. History and current status of the motor vehicle energy labeling and its implementation possibilities in Malaysia. J Renew Sustain Energy Rev 2012;16:1828–44.
[8] Silva CM, Baudoin J-M, Farias TL. Full life cycle analysis of different vehicle technologies. In: FISITA 2008 – 32th FISITA world automotive congress. Munich, Germany; 2008.
[9] Sullivan JL, Gaines L. Status of life cycle inventories for batteries. Energy Convers Manag 2012;58(0):134–48.
[10] Baptista P, Ribau J, Bravo J, Silva C, Adcock P, Kells A. Fuel cell hybrid taxi life cycle analysis. Energy Policy 2011;39(9):4683–91.
[11] Baptista P, Tomás M, Silva C. Hybrid plug-in fuel cell vehicles market penetration scenarios. Int J Hydrog Energy 2010;35(18):10024–30.
[12] Weiss MA, Heywood JB, Drake EM, Schafer A, AuYeung FF. On the road in 2020. Cambridge, Massachusetts: MIT; 2000.
[13] Zamel N, Li X. Life cycle analysis of vehicles powered by a fuel cell and by internal combustion engine for Canada. J Power Sources 2006;155(2):297–310.
[14] Goedkoop M, Oele M, Schryver Ad, Durksz S, Roest Dd. Introduction to LCA with SimaPro 7; 2010.
[15] Burnham A, Wang M, Wu Y. Development and Applications of GREET 2.7 Argonne National Laboratory; 2006.
[16] Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH. Comparative environmental life cycle assessment of conventional and electric vehicles. J Ind Ecol 2013;17:53–64.
[17] Elgowainy A, Burnham A, Wang M, Molburg J, Rousseau A. Well-to-wheels energy use and greenhouse gas emissions analysis of plug-in hybrid electric vehicles, ANL/ESD/09-2, Argonne National Laboratory; 2009.
[18] Burnham A. Updated vehicle specifications in the GREET vehicle-cycle model. Argonne National Laboratory; 2012.

[19] Geerken T, Timmermans V, Laussaux S. Hydogen and its applications: review of life cycle assessement and well-to-wheel studies. Hysociety Project (EU, 5th FP); 2004.
[20] Delucchi Mark A. A lifecycle emissions model (LEM): lifecycle emissions from transportation fuels, motor vehicles, transportation modes, electricity use, heating and cooking fuels, and materials. MAIN REPORT.ITS-Davis. Publication no. UCD-ITS-RR-03-17-MAIN REPORT; 2003.
[21] Lipman TE, Delucchi MA. Expected greenhouse gas emission reductions by battery, fuel cell, and plug-in hybrid electric vehicles. Electric and hybrid vehicles. 2010 (chapters 5 and 4.4.3).
[22] Silva C. Grid electrified vehicles: performance, design and environmental impacts. New York: Nova Publishers; 2013.
[23] ADIT. Green Vehicle Guide ⟨http://www.greenvehicleguide.gov.au⟩ [accessed January 2014].
[24] CleanerDrive. Report on vehicle environmental rating – deliverable d6; 2004.
[25] Timmermans J-M, Mathews J, Mierlo J, Lataire P. Environmental rating of vehicles with different fuels and drive trains: a univocaland applicable methodology. Eur J Transp Infrastruct Res 2006;6(4):313–34.
[26] Bewertung der PKW. VCD Auto-Umweltliste; 2012.
[27] Delucchi MA. The annualized social cost of motor-vehicle use in the United States, 1990–1991: summary of theory, data, methods, and results. UCD-ITS-RR)96-3. ITS Davis; 2004.
[28] Delucchi MA. A multi-country analysis of lifecycle emissions from transportation fuels and motor vehicles. California: University of California; 2005.
[29] Vaidyanathan S, Langer T. Rating the environmental impacts of motor vehicles: ACEEE's Green Book® Methodology. American council for an energy-efficient economy 2011.
[30] ExternE project. Method for Estimation of Physical Impacts and Monetary – Externalities of Energy, vol. 2 – methodology. Luxembourg: European Commission, DG XII; 1997.
[31] Lewis CA. MEET Project: Methodologies for Estimating Air Pollutant Emissions from Transport. ETSU Report No. R112, 1997.
[32] Montgomery Douglas C, Runger George C. Applied statistics and probability for engineers. 5th ed. Wiley, USA; 2010.
[33] Lane B. Life Cycle Assessment of Vehicle Fuels and Technologies. Final report 2006.